Physics and Chemistry of the Earth 109 (2019) 9–25

Contents lists available at ScienceDirect

Physics and Chemistry of the Earth

journal homepage: www.elsevier.com/locate/pce

Development and testing of a rainfall-runoff model for flood simulation in dry mountain catchments: A case study for the Dez River Basin

A. Samadi[a,*], S.S. Sadrolashrafi[b], M.K. Kholghi[c]

[a] Water Engineering Department, Faculty of Agriculture and Natural Resources, Imam Khomeini International University, Qazvin, Iran
[b] Water Resources Technician, Iranab Consulting Engineers Company, Tehran, Iran
[c] Irrigation and Reclamation Engineering Department, Agricultural Engineering and Technology Faculty, University of Tehran, Iran

ARTICLE INFO

Keywords:
Rainfall-runoff
Modelling
Hydrologic
WMS
GIS

ABSTRACT

Studying the rainfall-runoff response of the catchments has several important reasons in hydrology. The main reason is limitation of hydrologic parameters that can be measured in hydrological system. Therefore, the model that can estimate the transformation of rainfall to runoff with available range of measurements, particularly to limited gauged catchments can provide a means of prediction that will be useful in decision-making. Now days, various models have been developed around the world to model individual hydrological processes. In this study, the Watershed Modelling System (WMS) software was applied for rainfall-runoff modelling on Dez catchment located in Khuzestan province, IRAN since it faces serious flooding caused by heavy rainfall. The use of WMS software which interconnects the terrain models and the Geographic Information System (GIS) with commercial standard hydrological model including HEC-1 results in higher accuracy and saving time through modelling process. In this study, two historical storms (7 days in March 1993 and November–December 2001) used by applying two different modelling methods to determine the hyetographs which are one part of hydrologic process performing runoff response. Data collected from 29 November to 5 December 2001 were used for the calibration and the model verification were done for the period of 2–7 March 1993. Watershed parameters are calibrated manually to perform a successful simulation of discharge at three sub-basins in DEZ catchments. The outputs of hydrologic process using each method compared with observed data and the model performance were tested using statistical analyses. Considering the importance of parameters uncertainty and its effects on the response of the model, the sensitivity analysis was performed and the parameter which imposed the most impact on the model was identified. It was found that *CN* and *STRTL* parameters are the most important parameter in defining the peak flow, runoff volume and time to peak for all investigated methods in the studied basin. Sensitivity analysis reduces the complexity and uncertainty of hydrological simulations and provides a better understanding of the consistency between output and input in hydrologic modelling studies. The results of this research will benefit future modelling efforts by providing validated hydrological software to forecast hydrograph flooding on a regional scale. This model was designed for the Dez catchments, and this regional scale model could be used as a prototype for the model applications in other areas where lack of data exist.

1. Introduction

A major challenge remaining in hydrology is the accurate prediction of catchment runoff responses to rainfall events (Bürger et al., 2007). Therefore, hydrologic models are generally used all over the world (e.g. Singh, 1995). Modelling and prediction of this hydrologic process can help exploitation and managing the watersheds in the correct way. Moreover, they lead to effectively mitigate inundation that caused by floods. Difficulties in measuring catchment rainfall and runoff are usually worst in very big runoff events (Boughton, 2006). This issue becomes more important because many catchments around the world are ungauged or they have a limited gauge for measuring parameters and estimating runoff for these catchments is challenging (Pool et al., 2017).

Computer simulation of catchment water balance for estimating runoff from rainfall began in the early 1960s (Boughton, 2005). The numerous hydrological models which already exist vary in their model construction, partly because the models serve somewhat different

* Corresponding author. Water Engineering Department, Faculty of Agriculture and Natural Resources, Imam Khomeini International University, P.O. Box: 34148-96818, Qazvin, Iran.
E-mail addresses: samadi@eng.ikiu.ac.ir (A. Samadi), s.sarasadr@gmail.com (S.S. Sadrolashrafi), kholghi@ut.ac.ir (M.K. Kholghi).

https://doi.org/10.1016/j.pce.2018.07.003
Received 6 December 2017; Received in revised form 17 June 2018; Accepted 17 July 2018
Available online 26 July 2018
1474-7065/ © 2018 Elsevier Ltd. All rights reserved.

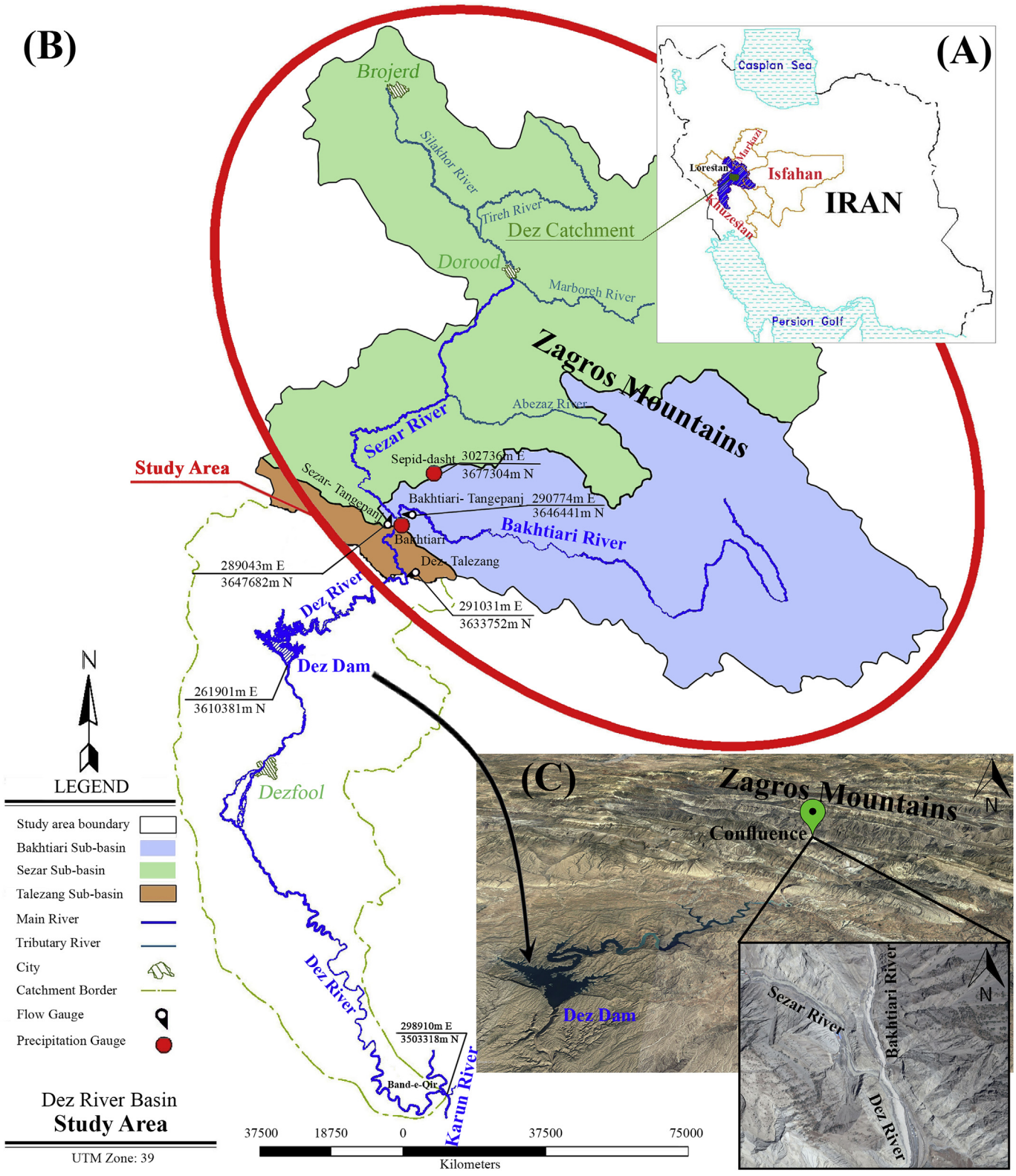


Fig. 1. Study area. (A) Location map of the catchment in IRAN, (B) Dez river basin, gaging stations and location of the study site along with geographical coordinates of some places in the UTM system (Zone 39) (C) 2017 aerial photograph from Google Earth showing the study site and the confluence.

purposes. There are models for design of drainage systems, models for flood forecasting, models for water quality, etc. (Singh and Woolhiser, 2002). In order to model rainfall-runoff process, different types of hydrological models can be used. Hydrological models are defined as mathematical representations of the water flow and its constituents on some parts of the land surface or the sub-surface environment (Maidment, 1993). Hydrologic models attempt to simulate the rainfall-runoff process to indicate "how much water, how often". These models make use of the rainfall information or simulations to provide the runoff characteristics including the peak flow, flood hydrograph and

flow frequencies (Haubner et al., 2001). Rainfall-runoff modelling has been proposed by several researchers, e.g., Bhaskar et al. (2005) used the TOPMODEL for the rainfall-runoff response in Tygarts Creeks Catchment in eastern Kentucky, USA, or Caruso et al. (2013) evaluated application of the HEC-HMS model by modelling flood events in a mountainous catchment in the New Zealand, and etc.

Since no universal model which could be used in all applications exists, it is necessary to consider alternative models to simulate specific application. The applicability of a model depends on the parameters which should be physically measured for a mathematical equation of the model and the ability to accurately estimate certain obtained results such as the peak discharge of the flood, its timing and duration. However, owing to their complex structure, a huge number of parameters and large data requirements, the application of these techniques has limitations. (Beven, 2001). The major source of error in any hydrological modelling is the uncertainty in the determination of model parameters, owing to the mismatch between model complexity and available data (Gupta et al., 2012; Zhang et al., 2012; Devak and Dhanya, 2017). A conceptually realistic and less data intensive hydrological model, MIKE 11 NAM was developed and tested using measured stream flow data of eight years from 1991 to 1998 for Yerli catchment (area = 15,701 km^2) of upper Tapi basin, Maharashtra in Western India. The sensitivity analysis indicated that runoff volume was found to be moderately sensitive with maximum water content in surface storage (Loliyana and Patel, 2015). To explore the performance of three different hydrological model concepts, Rogelis et al. (2016) used a lumped model (HEC-HMS), a semi-distributed model (TOPMODEL) and a distributed model (TETIS) to simulate the discharge response of a tropical high mountain basin located in Bogotá (Colombia). The sensitivity analysis showed that TOPMODEL is the most sensitive model to rainfall variability, albeit the most realistic model. Furthermore, the HEC-HMS soil moisture accounting producing ensembles in a range lower than the other two similar models (e.g., TETIS & TOPMODEL). Hoseini et al. (2017) comparing the ability of TR-20, TR55, and HEC-1 sub-models of WMS for a plain basin located in Southwest Iran, reported that TR55 method recorded the highest agreement with empirical values of that region.

Since the event-based rainfall–runoff models require less parameterization and more simple than continuous simulation approaches (Berthet et al., 2009; Coustau et al., 2012; Massari et al., 2014), they are more widely applied in hydrological simulations. Despite all these benefits, the major limitation of these models is the difficulty in assessing the antecedent soil moisture conditions, which can be very different from one storm event to the next (Hino et al., 1988; Tramblay et al., 2010, 2012; Coustau et al., 2012; Van Steenbergen and Willems, 2013; Hoseini et al., 2017). Therefore, there is a clear need to reduce the uncertainties associated with the initial moisture condition in event-based flood forecasting and design flood estimation techniques.

Most measurements are limited by space and time, specifically in developing countries where basic data required for water resource assessment are limited and almost not exist in some cases. Therefore, assigning accurate number and rates to these different variables can be difficult. In ungauged basins, flood formation modelling process must be built up using simplified descriptions of the hydrological processes characterized by a reduced number of robust parameters to ensure a reduced uncertainty in model predictions (Wagener et al., 2004). Therefore, it is important to develop realistic models that can be applied to ungauged or limited gauge catchments where a historical record of stream flow is not completely available. The modelling framework presented in this study demonstrates the accuracy and usefulness of the WMS software in estimation and prediction of runoff which is generated in catchments by rainstorms. This project was conducted in Dez River Basin during two different 7 days storm events. The observed data (stream flow) from the three gauging stations at the outlet of each sub-basins was used in the calibration/verification of the model. The period of 29 November to 5 December 2001 was used for the calibration and 2 to 7 March 1993 was used for the verification of the model.

2. Materials and methods

2.1. Geographical and hydrological description of the study area

The study area where has been selected for model development, is a part of Dez River Basin in Khuzestan province, south west of Iran which is located at the latitude of 29–33° N and longitude of 47–50° E (Fig. 1). Dez River is one of the most important branches of Karun River, originating from the highlands of Brojerd (Silakhor River) and Aligudarz (Marboreh River), and join with several other ephemeral tributaries extending to the south (in mountainous areas), with 520 km length and averages 258 m^3/s flow annually from wellhead up to Talezang Station with 16,213 km^2 catchment's area. This river enters the plain of Khuzestan after the Dez Dam, north of Dezfool and joins the Karun River in northwest of Ahvaz (Band-e-Qir at Fig. 1). The vegetation cover is low in the low altitudes of the basin, and with increasing height, the density of this cover is increased. In general, the most important plant species in the margin and inside the river are composed of different species (e.g., Juncus, Salix, Typha, grass, etc.), while some types of tree, shrub, and pasture species on the river banks and near the banks (e.g., Calligonum comosum, Seilitzia rosmarinus, Crataegus astrosanguinea, etc.). Table 1 presents the specifications of Dez River sub-basins, locations of flow and precipitation gauges.

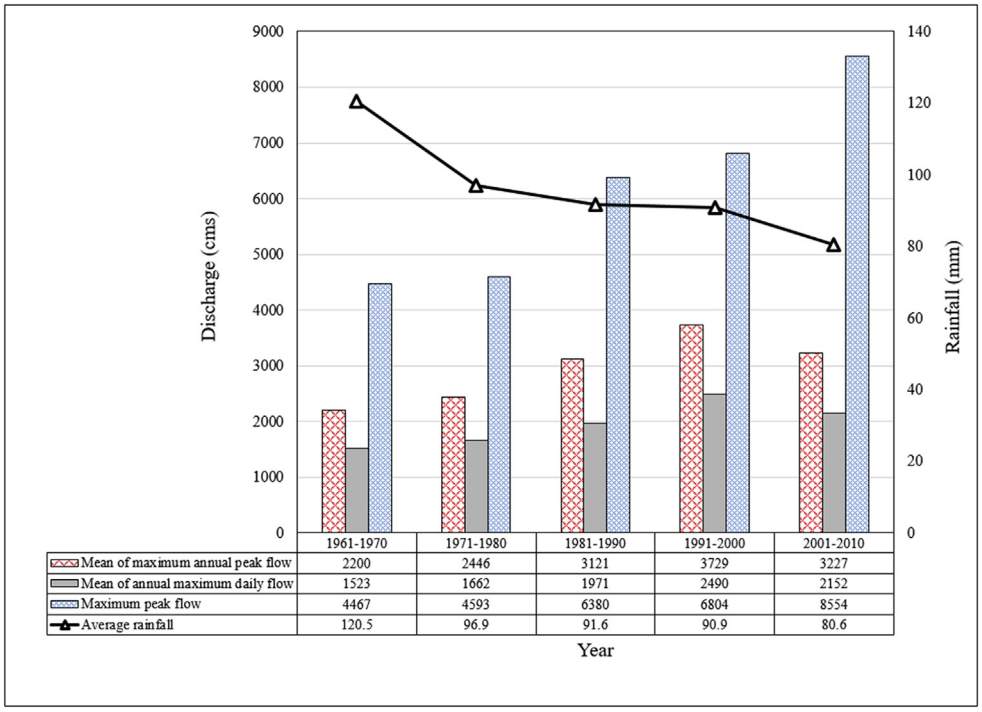
The 24-h rainfall pattern in the catchment area of the Dez River and its adjacent areas is 0.1–5 mm (weak), 5–10 mm (mild), 10 and 30 mm (moderate), and often severe 24-h rainfall over 30 mm. It is observed that the Bakhtiari sub-basin has less area than the Sezar (seventy percent less), but the average annual rainfall is 40 percent higher. Because the average height of the Bakhtiari is higher than Sezar sub-basin (Table 1). The average height of the Dez basin is 1976 m, and the maximum and minimum are 4124 and 19 m above sea level, while the Gravelius compactness index was found to be 1.71. The average annual precipitation in the north and east of the Dez River Basin is higher than in other areas of the basin. In terms of precipitation distribution, 48.8% of annual rainfall is observed in the winter, 30.6% in the autumn, 20.4% in the spring, and only 0.2% of precipitation in the summer.

The Dez River originally begins with connecting the main tributaries of the Tireh and Silakhor Rivers, with the addition of the Marboreh River, the Sezar River is formed. After joining the Abezaz River with Sezar River downstream of Dorood City, at a confluence location named Tangepanj inside the Zagros Mountains, Dez River is formed which is the confluence of the Sezar and Bakhtiari Rivers. The latter is the second main tributary of the Dez River, which is 40 km south of the Sorkhab River connecting to the Sezar River. In Khuzestan plain after

Table 1
Specifications of sub-basins in Dez River Basin.

Sub-basin (River)	Hydrometric station	Catchment area (km^2)	Average annual rainfall (mm)	Average elevation (m)	Observation period	Annual flow (MCM)
Bakhtiari	Tangepanj	6507	1032	2460	1977–2016	4830
Sezar	Tangepanj	9410	632	1667	1955–2016	3999
Dez	Talezang	16,213[a]	784	1976	1955–2016	9000

[a] The area of the middle sub-basin (between Talezang and confluence) is about 296 square kilometers.



	1961-1970	1971-1980	1981-1990	1991-2000	2001-2010
Mean of maximum annual peak flow	2200	2446	3121	3729	3227
Mean of annual maximum daily flow	1523	1662	1971	2490	2152
Maximum peak flow	4467	4593	6380	6804	8554
Average rainfall	120.5	96.9	91.6	90.9	80.6

Fig. 2. A brief analysis of the discharge and rainfall recorded data at Talezang station (basin outlet) for the last half century.

Dez dam (outside of study area), with decreasing slope of the land, the shape of the river bed has been transformed into meander (see Fig. 1 for detail), its cross-sectional area has increased significantly and the flow velocity has decreased.

Dez River is subjected to occasional flooding which causes serious damages. This river carries huge amounts of runoff from large areas such as Lorestan province which includes Borojerd and Dorood Cities, Khuzestan Province which includes Dezfool city, and Isfahan Province which includes Fereydoon Shahr City. Fig. 2 shows the amount of annual rainfall received in this area in the first decade of the 21st century has been less or equal than the last decades, but the flood intensity is increasing. The average rainfall corresponding to the floods of the 1960s is 120 mm and the average peak flow discharge is 2200 cms (i.e., cubic meter per second). Compared to these values, the average rainfall of the 2000's is 80.6 mm, and the average peak flow discharge is 3227 cms (noted that values of 4467 and 8554 cms recorded as maximum peak flow at the beginning and end of this 50 year period). According to this figure, atmospheric rainfalls from the mid-1960s has a decreasing trend. The results show that peak flow discharge has increased over the past 50 years, and it is expected that more severe floods will now occur. For example, peak flow discharge into the Telezang station was recorded at 6700 cms in 1997, but on April 14, 2016, the instantaneous peak discharge at this station reached an unprecedented record of 10,400 cms and its hourly discharge reached 8250 cms. The record of the maximum daily discharge rate of this station was 3172 cms in 2003 and with the average daily discharge recorded at 4437 cms in 2016, indicating a “catastrophic flood” occurred in this region.

According to the hydrometric data, about 50% of the Dez River discharge at the Talezang station is related to the Bakhtiari sub-basin and 42% of it is from the Sezar sub-basin. Approximately 2 h have been observed when the flood flows from the confluence of Bakhtiari and Sezar to the Talezang Station. Hourly readings of hydrographs indicate a slight difference in flood peak time in three sub-basins of Bakhtiari, Sezar and Dez, which is usually observed for about 2–4 h. The long-term trend of hydrological events along with 290 flood events in the Dez River basin have been evaluated for a 50 years period (1955–2005). Results indicate that the peak flow of 17 flood events (52% of the total floods) were over 2900 cms from 1991 to 2005, while these values were normal from 1955 to 1990 (Sourinejad, 2008).

Dez Catchment headwater to Talezang Station is highland and water channel is anfractuous with steep slope. There were two temporal distribution gauges which estimated the rainfall intensities at 1-min steps for the entire study area under the names of Bakhtiari and Sepid-dasht, which are mostly mountainous and cumbrous (See Fig. 1 for detail). Therefore, installing more gauges and gathering data was hard and impossible, especially in the cold seasons. Moreover, there were no other precipitation gauges that could be used for this research in or near the study area. Although the study area has limitations in distribution of precipitation gauges, the attempt to simulate this limited data is valuable. On the other hand, most of the countries, mainly in the developing world, still lack of historical data and facilities to measure it. Therefore, acceptable modelling results using limited precipitation gauge in watersheds can be applicable for other regions that have limited precipitation gauge problem. Three stream gauges were used in this study, i.e., Tangepanj-Bakhtiari is located at the outlet of Bakhtiari sub-basin; Tangepanj-Sezar is located at the outlet of Sezar sub-basin and Talezang-Dez is located at the outlet of Talezang sub-basin and the outlet of all three sub-basins (Their geographic locations are presented in Fig. 1). Each of these gauges contain full range of data to establish observed hydrographs. The watershed area, elevation (DEM contours), flow gauges, and streams are seen in Fig. 3. Furthermore, topography map, Digital Elevation Model (DEM) with a resolution of 50 m and Land Use/Land Cover (LULC) shapefiles were retrieved from Soil Conservation and Watershed Management Research Institute, IRAN. The land use information was derived from Landsat Thematic Mapper (TM) image using a Maximum Likelihood Classifier. The classification process results in a land use map having 15 land use classes (Fig. 4), i.e., agriculture (2.6%), dry farming (0.9%), dense forest (12.7%), moderate forest (13.6%), low forest (12.9%), garden (0.4%), woodland (0.6%), good range (9.1%), moderate range (19.2%), poor range (6.2%), rock (1.0%), urban (0.3%), water surface (0.04%), agriculture-dry farming mixture (19.4%) and good range-agriculture mixture (1.0%).

The temporal extent of the study was selected from March 2, 1993

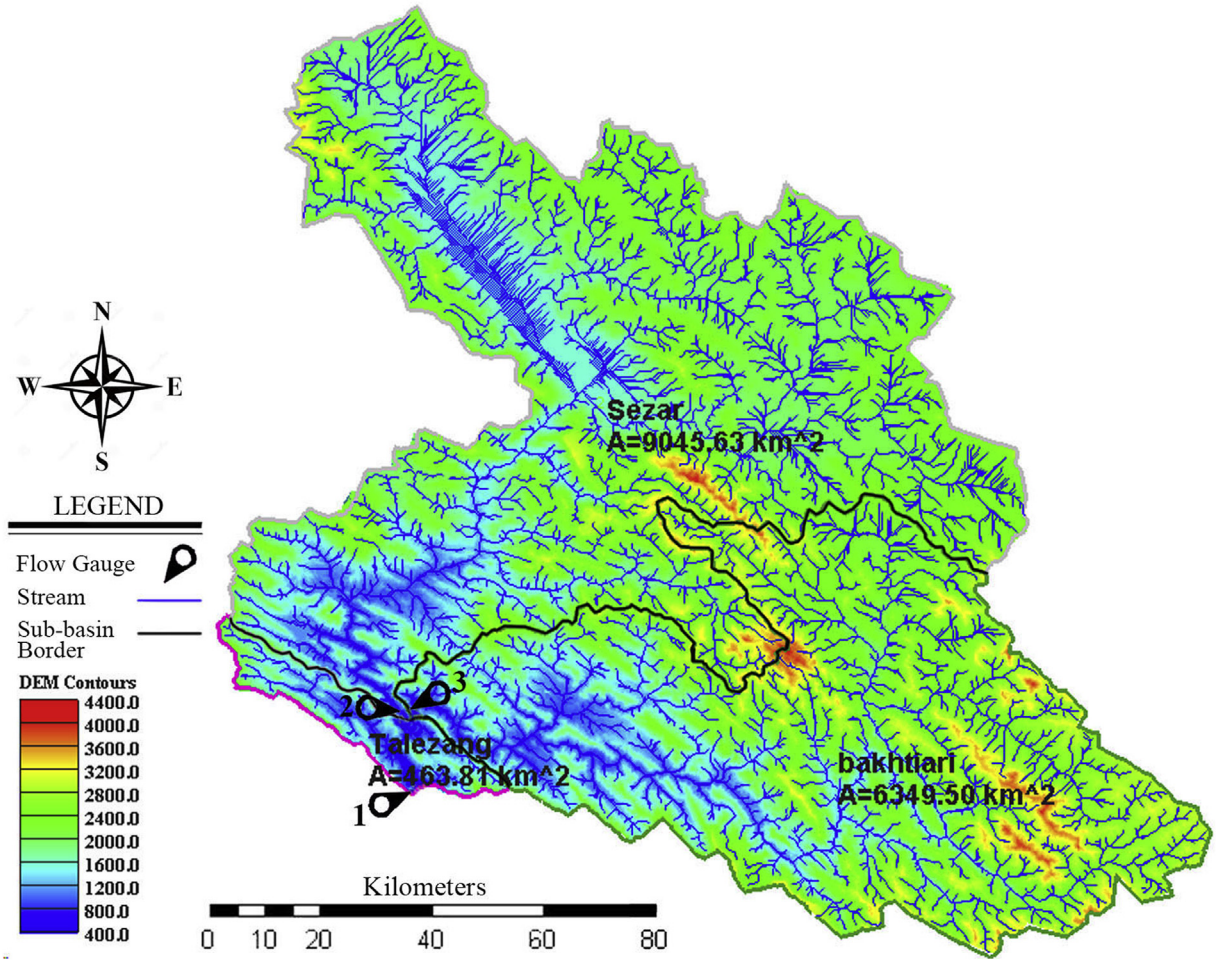


Fig. 3. Watershed Digital Elevation Model (DEM) map, distribution of rainfall and stream gauges.

to March 8, 1993 and November 29, 2001 to December 5, 2001, to cover the duration of storms. The 2001 flood was used for model calibration and another one (1993) was used to verify the model. The first storm (2001) has a duration of 44 and 42 h in Bakhtiari and Sezar sub-basins, respectively, however the intensity was 4.2 and 1.9 mm/h for Bakhtiari and Sezar, respectively. In the second storm (1993), duration of 44 h has been recorded for both sub-basins, with the intensity of 3.9 and 1.8, respectively. In both events, the rainfall intensity in the Bakhtiari sub-basin is more than twice the Sezar sub-basin, and although its area is 30% less than Sezar, the rainfall in Bakhtiari was more than twice Sezar. Table 2 shows the characteristics of both events, such as start and end time of storm, duration, intensity, and rainfall depth.

The information used in this project includes: rainfall data obtained from digital gauges in the basin, and this data was gathered from two sources: Water Resource Management Organization in Tehran and Water & Power Organization in Khuzestan; three stream flow gauges with complete hydrological datasets formed a base of stream flow observations over the study region, including discharge measurements and other basin parameters came from Dezab Consulting Engineers Company.

2.2. Model description

Rainfall-Runoff model (HEC-1): Runoff is modeled by HEC-1 flood hydrograph package, a computer program originally developed in 1967 by Leo R. Beard and other members of the Hydrologic Engineering Center (cited in Hydrologic Engineering Center, 1998). HEC-1 is accepted by the Federal Emergency Management Agency; it is therefore the most widely used model for analyses of major drainage systems (Haubner et al., 2001). The U.S. Army Corps of Engineers now uses HEC-HMS rather than HEC-1, but hydrologic calculations for the options within HEC-1 have not changed. Results of the two models will be identical (Brigham Young University, 2002).

WMS (Comprise all modules): The WMS is a comprehensive environment for hydrologic analysis. It was developed by the Environmental Modelling Research Laboratory at Brigham Young University, in co-operation with the U.S. Army Corps of Engineers Waterways Experiment Station (Brigham Young University, 2002; EMSI, 2008). WMS includes powerful tools to automate modelling processes such as automated basin delineation, geometric parameter calculations, GIS overlay computations including curve numbers (*CN*), rainfall depth, roughness coefficients, etc., and cross-section extraction from terrain data. WMS provides an interface for a variety of hydrologic and hydraulic models within a GIS-based processing framework. Models packaged within the system include HEC-1, TR-20, TR-55, National Flood Frequency Model (NFF), Modified Rational Method Model (MODRAT), OC Rational, and HSPF as hydrologic modelling components. HEC-RAS, Simplified Dam-Break Model (SMPDBK), and CE QUAL W2 provide hydraulic modelling capabilities. Gridded Surface Subsurface Hydraulic Analysis (GSSHA), a runoff and infiltration model from the U.S. Army Corps of Engineers (USACE) Engineering and Research Development Center (ERDC), is also included for 2-D integrated hydrology modelling with groundwater interactions. Additional calculations include use of the rational method to compute peak flows primarily for small rural watersheds (EMSI, 2008). The hydrologic models

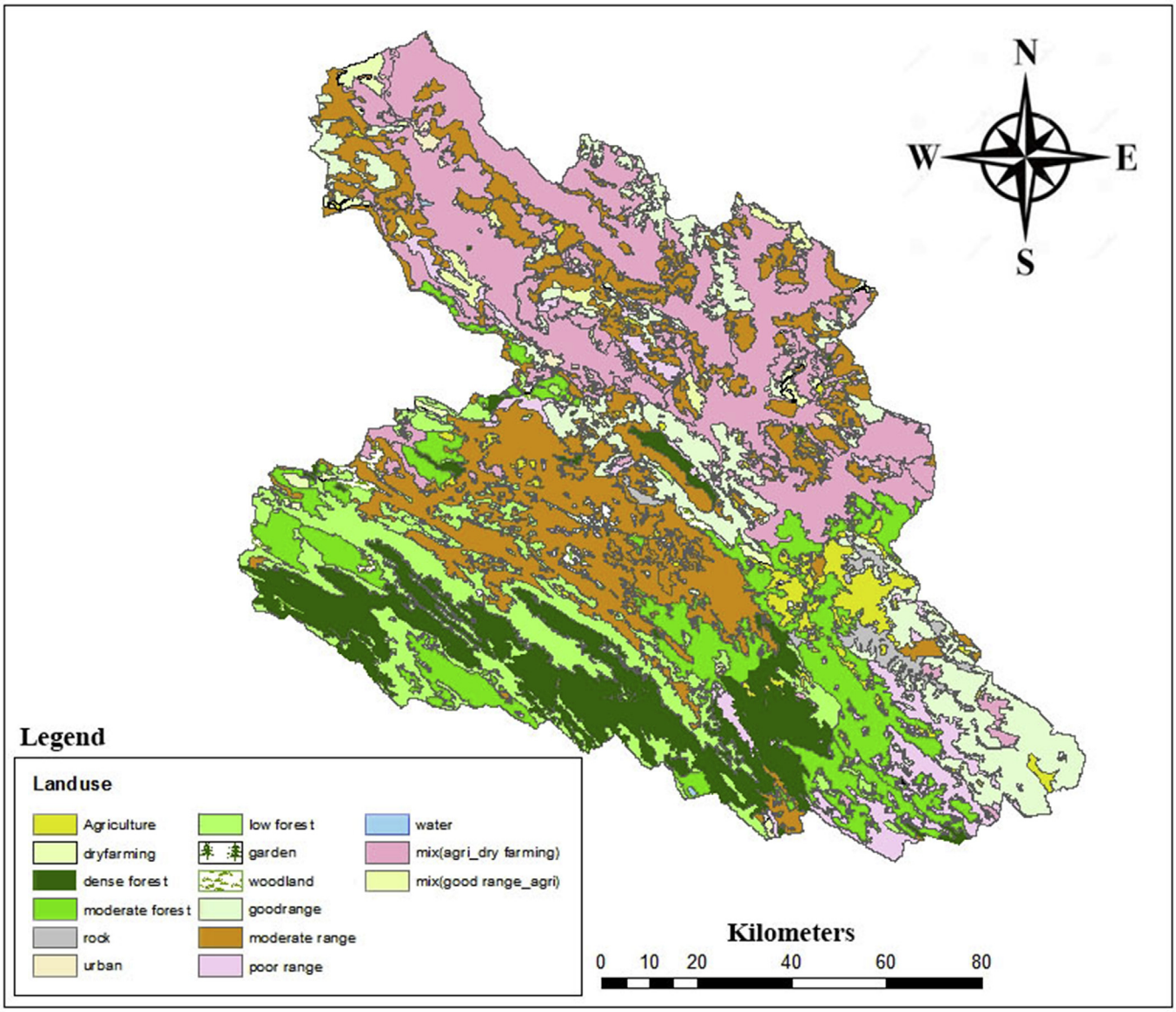


Fig. 4. The land use map of the Dez river basin.

Table 2
Characteristics of the two selected storm events.

Sub-basin	Station	Storm	Start Time	End Time	Duration (hr)	Intensity (mm/hr)	Rainfall Depth (mm)
Bakhtiari	Bakhtiari	11/29/2001	20:40	16:40	44	4.2	186.4
		3/2/1993	14:40	10:40	44	3.9	172
Sezar	Sepid-dasht	11/29/2001	17:15	11:15	42	1.9	85.2
		3/2/1993	11:40	7:40	44	1.8	79

can be run using the WMS interface. The link between the spatial terrain data and the hydrologic model(s) gives users the ability to develop hydrologic data which are typically gathered using the manual methods. For example, when using the Soil Conservation Service (SCS) methodologies, watersheds and sub-basins can delineate areas and curve numbers, determine and calculate time of concentration in the computer. These computations are typically done manually, which is rather laborious and time-consuming (Haubner et al., 2001). WMS is capable of importing and exporting information from terrain models. The advantage of using this type of hydrologic models is that flow and stage can be computed automatically with a high accuracy within the model domain.

Processing steps: The methodology used for this research is illustrated in Fig. 5. The first step in the WMS model is to provide a basin model that is prepared by the GIS pre-processing step using the DEM and land use map. This basin model is the base of hydrological and hydraulic models and delineating flood hazard map. The process in the analysis of the terrain data, which leads to creation of the basin model, is:

- Importing features from the GIS and converting DEM to a special DEM format compatible with WMS software;

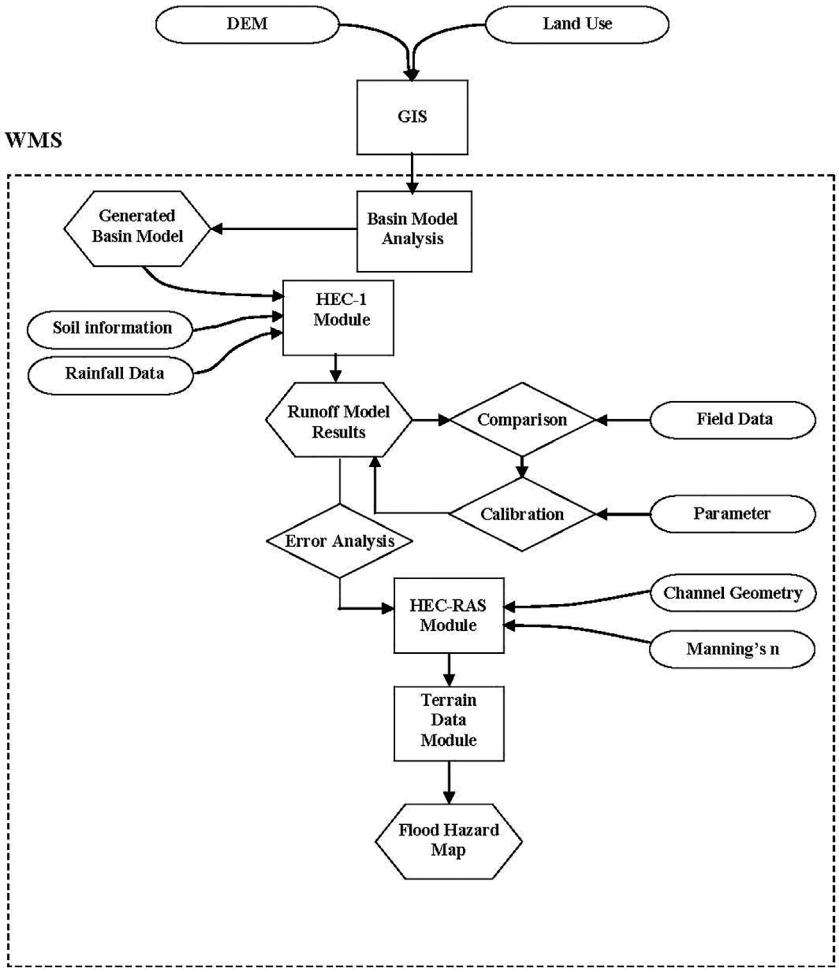


Fig. 5. Research Methodology (Note: Different steps in HEC-1 model are described in Fig. 6) (cited in Sadrolashrafi, 2008).

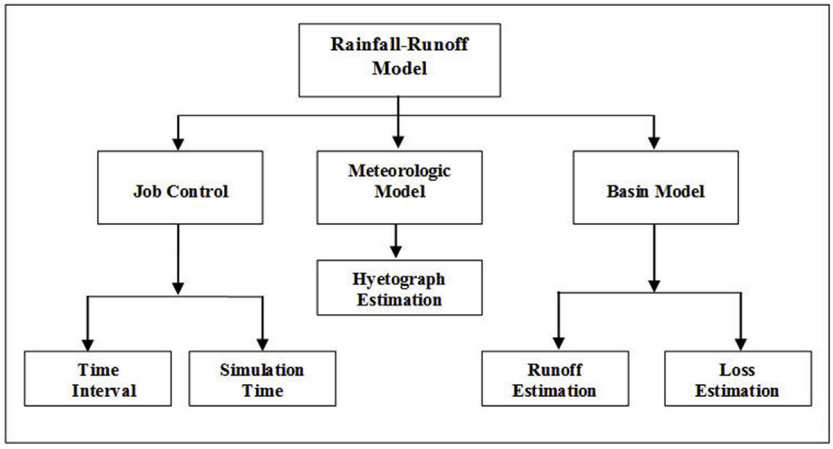


Fig. 6. Rainfall-Runoff modelling procedure in HEC-1.

- WMS uses TOPAZ (TOpographic PArametriZation) to compute flow directions and flow accumulations for using in basin delineation with DEMs. The TOpagraphic PArameteriZation (TOPAZ) program was developed by the USDA-ARS, National Agricultural Water Quality Laboratory (Brigham Young University, 2002).
- In order to delineate watershed, WMS converts the TOPAZ stream into the stream feature arcs, and then using them to define basin. In order to delineate a sub-basin, outlets were defined for the sub-basins. Finally, Polygons were created from the DEM basin.
- As the DEM contains elevation data, WMS used the model to automatically compute the drainage data such as the basin area, basin slope, basin length and the maximum stream length.

The basin model delineated for the study area is depicted in Fig. 3.

The WMS model is composed of several modules that can be used for flood inundation mapping along the river while converting rainfall depth into runoff volume and hydraulic routing. Focus of this study is on the ability of this model to convert rainfall to runoff and provide

flood hydrograph for flood warning systems, and finally, the sensitivity of various parameters in this simulation will be evaluated. The last step of this flowchart (Fig. 5) used in this study is the error analysis section. The full details of the model flowchart are given by Sadrolashrafi (2008). For the current simulation, the HEC-1 module is used as the main transformation of the modelling process. HEC-1 is basically a lumped parameter flood hydrograph program which was preferred here due to its simplicity and limited data access in our studied basin. In HEC-1, the identification of the modelling elements is done using the WMS Code, which is a text string used within HEC-1 module to identify each model feature (known as the Hydrologic Element in the WMS for hydrologic process).

The hydrologic simulation (Rainfall-runoff model, Fig. 6) comprised of basin model, meteorological model and control specifications. The basin model was used to import the DEM map from the GIS, edit the information and delineate watershed basins which served as the base for the simulations. Only one basin model was created to be used for all the rainfall events. The meteorological model related to precipitation methods (transformation of rainfall to runoff), the two methods which were used to produce hyetograph and evaluate methods by comparing predicted and observed hydrographs, including the gage weight (Method 1), and basin average (Method 2). The job control component which contains the starting time of storm, the duration of simulation and interval duration, was filled for each storm; for this purpose, 120 min was used as the time interval providing enough time to avoid losing volume of hydrograph.

Excess precipitation was estimated with the Soil Conservation Service Method, while the transformation of rainfall to runoff was calculated using the Unit hydrograph Method and Muskingam-Cunge method was used for routing the excess rainfall over the overland flow Plaines. Once the set up of these components was completed, they were used to run the hydrologic model. This methodology was repeated for every sub-basin and storm. The calibration process was carried out to match the result of the December 2001 storm using the observed data. The March 1993 storm was run without changing the parameter to ensure the accuracy of the calibrated model. Similarly, the error analysis was performed for the results derived from the model to compare the accuracy of models, as well as identify the best method. Different steps in rainfall-runoff transformation using HEC-1 module are also shown in Fig. 6 and described as follows:

The Gauge Weight Method (Method 1): One of the basic requirements in hydrological studies is an accurate value of the average precipitation applied over the watershed during the storm events. For this study, both the rainfall depth and temporal distribution were used. This method used Sepid-dasht and Bakhtiari gauges for the Sezar and Bakhtiari basins, respectively. Due to the lack of the gauge for the Talezang sub-basin, the nearest gauge, i.e. Bakhtiari gauge was used as its precipitation gauge.

At first, the geographic coordinates of gauges need to be identified. In this method, perpendicular bisectors are drawn through the straight lines joining adjacent gauges, leaving each gauge in the center of polygon, which varies in size according to the spacing of the gauges. The percentage of the total catchment area represented by each polygon or part of a polygon is calculated and applied to the appropriate rain gauge total rainfall. With the terrain model, WMS has the ability to automatically compute gauge weights (using Thiessen polygon method) for each basin. The gauge weights can be changed/assigned manually on the gauge weights button in the precipitation dialog (Brigham Young University, 2002). This is an area-based weighting scheme, based on the assumption that the precipitation depth, at any point within a watershed, is the same as the precipitation depth at the nearest gauge in or near the watershed. Thus, it assigns a weight to each gauge in proportion to the area of the watershed which is closest to that gauge. Weighted precipitation gauges are computed using the fallowing equation:

$$\mathrm{PRCPA} = \frac{\sum_{J=1}^{n} PRCPN(J) \times WTN(J)}{\sum_{J=1}^{n} WTN(J)} \quad (1)$$

Where PRCPA is the sub-basin average total precipitation, PRCPN (J) is the total precipitation for gauge J, WTN (J) is the relative weight for gauge J, and n is the number of gauges.

After performing the model and producing hydrograph for each sub-basin outlet, the values of the runoff calculated by the model with these weights were compared with the field data, and the new weights were chosen and re-introduced into the modelling system. This process was repeated until a good result was achieved for the December 2001 storm.

The Basin Average Method (Method 2): The simplest method is to calculate the arithmetic mean of the rain gauges in the area which can give adequate results, if the distribution of gauges exists (Brigham Young University, 2002).

Loss Estimation: Hydrological losses can be affected by the characteristics of rainfall, catchment geography (e.g. slope of the catchment and vegetation) (Hill and Mein, 1996) and soil moisture content. The Soil Conservation Service (SCS) Curve Number Method (*CN*) was used in this research to estimate the amount of rainfall which would be transformed to the runoff. The *CN* is a method for determining storm runoff over an area based on land use, soil and land cover type, and hydrologic soil group (US SCS, 1986). This method estimates the precipitation excess as a function of cumulative precipitation, soil cover and antecedent moisture using the following equation:

$$Q = (P - I_a)^2/((P - I_a) + S) \quad (2)$$

$$I_a = 0.2S \quad (3)$$

$$S = \frac{25400 - CN \times 254}{CN} \quad (4)$$

Substituting Eq. (3) into Eq. (1) gives:

$$Q = (P - 0.2S)^2/(P + 0.8S) \quad (5)$$

Where Q is runoff in (mm); P is rainfall in (mm); S is availability of soil moisture (mm); I_a is initial abstraction (mm); CN is runoff curve number (Hydrologic Engineering Center, 1998).

Runoff Estimation: HEC-1 automatically sets the duration of unit excess equal to the computation interval selected for the watershed simulation. The rainfall excess hyetograph is transformed to a sub-basin outflow by utilizing the general equation, as stated below:

$$Q(i) = \sum_{j=1}^{i} U(j) \times P(i - j + 1) \quad (6)$$

In which, $Q(i)$ is the sub-basin outflow at the end of computation interval i, $U(j)$ is the jth ordinate of the unit hydrograph, $P(i)$ is the average rainfall excess for computation interval i. The equation is based on two important assumptions. First, the unit hydrograph is a characteristic of a sub-basin and is not storm dependent. Second, the runoff due to excess from different periods of rainfall excess can be linearly superposed (Hydrologic Engineering Center, 1998). The SCS method was chosen in this study in order to compute unit hydrograph and Muskingum Cunge method for routing the hydrograph result.

SCS Dimensionless Unit Hydrograph: Input data for the Soil Conservation Service, SCS, dimensionless unit hydrograph method (US Soil Conservation Service, 1972) consists of a single parameter, i.e. TLAG, which is equal to the lag (hrs) between the center of mass of rainfall excess and the peak of the unit hydrograph (Hydrologic Engineering Center, 1998). The peak flow and time to peak are computed as:

$$T_{Lag} = \frac{L^{0.8}(S + 1)^{0.7}}{(1900)Y^{0.5}} \quad (7)$$

$$T_{Peak} = 0.5 \times \Delta t + T_{Lag} \quad (8)$$

$$Q_{Peak} = 0.208 \times \frac{A}{T_{Peak}} \quad (9)$$

- Here T_{Peak} is the time to peak of unit hydrograph in hours, t is the duration of excess in hours or computation interval, Q_{Peak} is the peak flow of unit hydrograph in cfs/inch, and A is the sub-basin area in square miles (Hydrologic Engineering Center, 1998).
- All computations in this part of process were done automatically because of the ability of WMS software to estimate required information using DEM. The ability of this software is valuable because of its high accuracy in estimating the T_{Lag}; the results of the simulation are therefore more authentic compared with the modelling software which is unable to compute this parameter with good exactitude.

Runoff Routing: The Muskingum Cunge method was used to route the rainfall excess over the overland flow planes after generating flood hydrograph for each sub-basin. Using the basin data computed by the WMS when a TIN or DEM is used to delineate the watershed, the L and S can easily be computed. Muskingum Cunge is essentially defined with the same parameters. A brief description is given as follows (Brigham Young University, 2002):

- L - Channel length
- S - Channel slope
- N - Manning's roughness
- Shape - Characteristic channel shape
- WD - Base width of the channel
- M − Side slope of channel

After executing the hydrologic model, the results can be displayed as hydrograph and table.

Model Calibration: The flood hydrograph results generated for each sub-basin were computed with HEC-1 model. The reliability of the model output depends on the parameter estimation and input data. Using a “basin-wide multiplier” (Vertessy et al., 2000) or a “reduction factor” (Giertz et al., 2006) is a common consideration in calibrating physically based parameters of distributed models, which can retain the spatial variability and simplify the model calibration. HEC-1 calibration is essentially performed by adjusting depression storage, infiltration, curve number (*CN*) and time lag for each sub-basin (Duru and Hjelmfelt, 1994). Adjustment of these parameters should be monitored to closely match the model behavior to the real world. The manual calibration uses a trial and error process of parameter changing which are essential in model result. After changing each parameter, simulated and observed hydrographs are compared to see how much the results have improved. WMS/HEC-1 was calibrated for the December 2001 event; the accuracy of adjusting parameter for the calibrated model was then examined with another flood event in March 1993.

Error analysis and model verification: For evaluating the performance of the model, multiple criteria can be used, depending on the purpose of the study. Each criterion has its own strengths and weakness, and the results of these criteria complement each other. The performance of the models used in this study, the gauge weight method (Method 1) and average method (Method 2) were evaluated using the statistical comparison of predicted and observed hydrographs. In this study, the following criteria were taken into account:

1. The percent error (Stewart, 2003)
2. The coefficient of determination (R^2)
3. The index of agreement (Willmott, 1981)

The prediction of the total runoff volume, time to peak and peak flow, had been compared with observed information. The error analysis was used to calculate the error of the predicted peak flow, time to peak and volume runoff. The percent error of these parameters has been used in many hydrologic modelling studies (Stewart, 2003). The percent error (relative error) in the peak flow, time to peak and hydrograph volume are defined from Stewart (2003) as in Eqs. (10) and (11):

$$Z = 100 \times \left(\frac{Y_{Peak} - X_{Peak}}{X_{Peak}} \right) \quad (10)$$

Where, Y_{PEAK} is the computed peak flow or time to peak, and X_{PEAK} is the observed peak flow or time to peak.

$$Z = 100 \times \left(\frac{Y - X}{X} \right) \quad (11)$$

Where, Y is the computed hydrograph volume, and X is the observed hydrograph volume.

The correlation coefficient (R^2) which estimates the efficiency of each method using in the model, is as Eq. (12). The correlation coefficient was used to determine the relationship between the computed and observed parameters. Obviously, a bigger R^2 value (close to 1) means a better fit of the predicted time series to the observed one.

$$R^2 \rightleftarrows = \rightleftarrows \left[\frac{\sum_{t=1}^{n} (O_{obs}^t - \rightleftarrows \overline{O}_{obs}) \rightleftarrows (O_{sim}^t \rightleftarrows - \rightleftarrows \overline{O}_{sim})}{\sqrt{\sum_{t=1}^{n} (O_{obs}^t - \rightleftarrows \overline{O}_{obs})^2 \sum_{t=1}^{n} \rightleftarrows (O_{sim}^t \rightleftarrows - \rightleftarrows \overline{O}_{sim})^2}} \right]^2 \quad (12)$$

Where Q_t^{obs} and Q_t^{sim} = the observed and simulated discharge at time t, respectively, $\overline{Q}^{obs}$ and $\overline{Q}^{sim}$ = average observed and simulated discharge, respectively, and n is the number of discharge data.

In addition to R^2, which is usually used as objective function for model validation, the index of agreement according to Willmott (1981) is applied. This index overcomes the insensitivity of E (coefficient of efficiency, proposed by Nash and Sutcliffe, 1970) and R^2 to differences in the observed and predicted means and variances (Legates and McCabe, 1999). It is a good indicator to evaluate the temporal representation of the discharge by the model. It is calculated with the following equation:

$$IA = 1 - \frac{\sum_{t=1}^{n} (Q_t^{obs} - Q_t^{sim})^2}{\sum_{t=1}^{n} (|Q_t^{obs} - \overline{Q}^{sim}| + |Q_t^{sim} - \overline{Q}^{sim}|)^2} \quad (13)$$

The range of values of the index of agreement is between 0 and 1, while 1 represents the total agreement of measured and simulated values.

2.3. Sensitivity analysis

The efficiency of the calibrated parameter can be clearly enhanced if it is possible to concentrate on the effort on the parameters in which the model simulation results are the most sensitive (Beven, 2001). A sensitivity analysis is done after the calibration to estimate whether the parameters are identified well or are poorly done (Clarke, 1973). Sensitivity analysis methods help to identify the parameters that have a strong impact on the model outputs and hence influence the model response. In addition, this analysis assists in analyzing the interaction between parameters, its preferable range and its spatial variability, which in turn influence the model outcomes. Identifying and ranking the effectiveness of the parameters on the results are crucial. Possible techniques for the pre- and post-calibration sensitivity analysis are such as the perturbation, the factorial, the Fourier Amplitude Sensitivity Test (FAST), or the Regional Sensitivity Analysis (RSA) methods (Wagener et al., 2004). For this study, the perturbation method was used. This method approximates sensitivities of the output variable to the perturbed parameter by differential quotients, based on the two runs of the model. The first run keeps all parameters constant; the second one with perturbed, while the single parameter values are increased or decreased by a constant amount within the range of the expected boundary condition, with the remaining fixed at their nominal or base line values. The initial parameter in this study was grouped in three categories:

Curve Number (*CN*), initial rainfall abstraction (*STRTL*) and percentage of drainage basin that are impervious (*RTIMP*). The expected boundary ranges are 30–100 for *CN*, 2–50 mm for initial rainfall abstraction and 0 to 20 percentage of drainage basin that are impervious. Sensitivity tests were performed to examine how these parameters affect the sensitivity of time to peak, peak flow and runoff volume.

Furthermore, to evaluate the sensitivity of model simulation results, the sensitivity index (SI_i) was also calculated according to de Roo (1993):

$$SI_i = \frac{|Q_{Pi} - Q_{Mi}|}{Q_o} \quad (14)$$

where,

Q_{Pi} = model output with i% increase of the parameter value,
Q_{Mi} = model output with i% reduction of the parameter value,
Q_o = model output with base simulation.

The percentages of perturbations are different in parameters due to their response in changing the output result. The December 2001 flood was chosen over other floods to perform the sensitivity analysis for this model. As characteristics of the models and used methods are the same in all floods, the results of the sensitivity analysis for the model can be used for these floods or any other flood data.

3. Results and discussion

In this study, a physically-based, lumped rainfall-runoff model was developed and tested for predicting storm runoff of dry mountain catchment. Once the set up of aforementioned components was completed, the hydrologic model was ready to run. For this study, the curve number (*CN*), time lag (*TLAG*), initial rainfall abstraction (*STRTL*), percentage of drainage basin impervious (*RTIMP*), and gauge weight were adjusted for the calibration process to produce an output hydrograph. Manual calibration was made for each sub-basin in this step. The input parameters were identified by comparing the measured and simulated hydrographs. After running the model, calculated gauge weights were changed to have the best fit between observed and calculated hydrographs and therefore modifying the runoff in the model. Table 3 shows the modified gauge weight effect on each sub-basin while using Method 1 for simulation. The three sub-basins show large differences in magnitude for the calibrated gauge weight method (Table 3). Sepid-dasht gauge which located in Sezar sub-basin has much effect on Bakhtiari sub-basin, however Bakhtiari gauge that located in Bakhtiari sub-basin has little effect on Sezar sub-basin. Also, Sepid-dasht gauge has no effect on Dez Sub-basin. The initial and calibrated values of the curve number (*CN*), initial rainfall abstraction (*STRTL*), percentage of drainage basin impervious (*RTIMP*), for all sub-basins are given in Table 4. These parameters were used in model study with the aim to include as much effective characteristics in the hydrological model as possible. Results of observation and calibration were compared and used for parameter sensitivity analysis. In the first step of calibration, the *CN* values were modified. Because the relationship between *CN* and concentration time values, the amount of concentration time has been improved and imposed by modifying the time of peak. Since each sub-basin have unique infiltration topography, soils, etc., time of concentration in some sub-basins was increased while in others was decreased from its calculated value. The calibration process was carried out to match the result of December 2001 storm using the observed data. The model computed the hydrograph results using the unit hydrograph method for December 2001 storm event.

Table 3
The modified gauge weight for each sub-basin (Method 1).

Sub-basin	Bakhtiari Gauge weight	Sepid-dasht Gauge weight
Bakhtiari	0.32	0.68
Sezar	0.05	0.95
Dez	1	0

Table 4
Initial and calibrated parameters of all studied sub-basins. All values refer to averages of the entire sub-basins over the studied time periods.

Parameter	Bakhtiari		Sezar		Talezang	
	initial	calibrated	initial	calibrated	initial	calibrated
CN (−)	75	64	77	69	76	65
STRL (mm)[a]	22	32	25	35	20	27.35
RTIMP (%)[b]	12	4	14	6	10	7

[a] *STRTL* = Initial rainfall abstraction.
[b] *RTIMP* = Percentage of impervious drainage basin.

March 1993 storm was used to verify the model using parameter values determined by calibration process. Comparison of observed and simulated hydrographs is shown in Figs. 7 and 8 for calibration and verification steps, respectively. It was seen that simulated flood hydrographs demonstrated a close agreement with the observed hydrographs at peak stage for both storm events and methods, while the verification phase is better, especially at the basin outlet (i.e., Talezang station). The initial uncalibrated hydrograph is shown by dash dot in Fig. 7, which has a significant difference with observation values at sub-basin outlet stations. For example, the peak flow has been predicted 3352, 3107, 6473 cms before calibration at Bakhtiari, Sezar, and Talezang sub-basins, respectively. While the observed values were 1944, 1724, 3668 cms, i.e., the model has a range of 70–80 percent overestimation in peak flow discharges. In all sub-basins, the time to peak is estimated to be more than 4 h earlier than its occurrence. Output results have a good agreement with observed values for all three sub-basins by calibrating the model. The error analysis was performed for the results derived from the model to compare the accuracy of two methods in the model, as well as identifying the best method. The model results and relative errors are also represented in Tables 5–7. Table 5 shows the simulated and observed peak flow along with percent errors for both methods used in this study. Tables 6 and 7 show volume and time to peak values with their relative errors for both storm events.

Comparing the simulated hydrographs in the calibration step with the corresponding observational values, it is seen that both methods in the simulation of the rising and falling limbs of hydrographs exhibit a large difference with the observed values, but they can properly model the hydrograph peaks, i.e., time to peak and peak flow discharge values. The Method 1 estimates the peak time without any error, although the basin average method (i.e., Method 2) has a marginal error only at the outlet (less than 4%). This method (i.e., gauge weight) simulates the peak discharge with acceptable accuracy (less than 10 percent error) relative to the corresponding observational values, however the Method 2 has an error rate of less than 5 percent that are both acceptable. In other words, the overestimation of the Bakhtiari sub-basin was depreciated with underestimation of the Sezar sub-basin, and at the outlet point (Talezang) the error value is less than 2%.

The main reason for the HEC-1 inability to predict the shape of the hydrograph is the weakness of these type of models. Rainfall-runoff models can be classified as lumped and distributed models based on the model parameters as a function of space and time (Devia et al., 2015). In lumped models, the entire river basin is considered as a single unit where the spatial distribution is neglected and hence the outputs are predicted regardless of spatial processes. This is while the distributed models perform their predictions based on the spatial distribution pattern (Moradkhani and Sorooshian, 2008). In this type of hydrological modelling useful in flood warning systems, i.e. a lumped parameter hydrologic and event-based model, the goal is to estimate the peak flow and time to peak, but the runoff volume (shape of

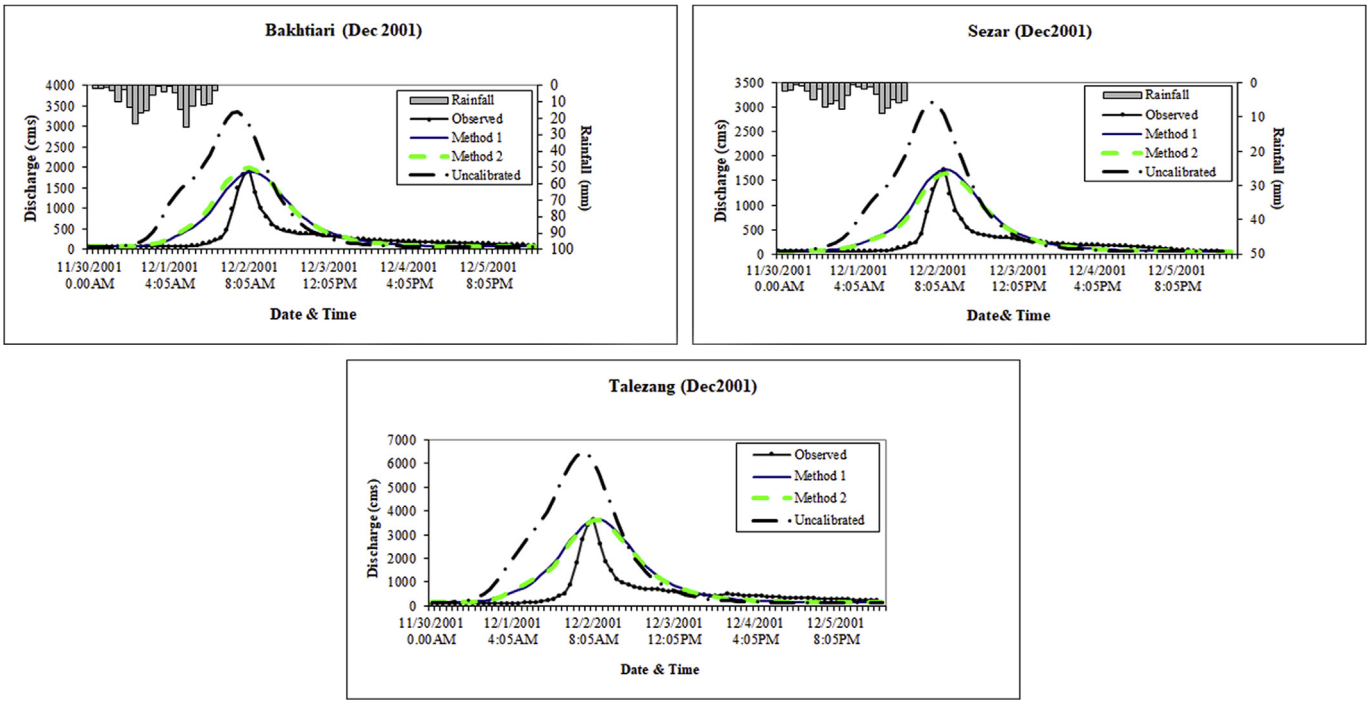


Fig. 7. Storm Dec 30, 2001, predicted vs. observed runoff hydrograph for sub-basins: (A) Bakhtiari, (B) Sezar and (C) Talezang.

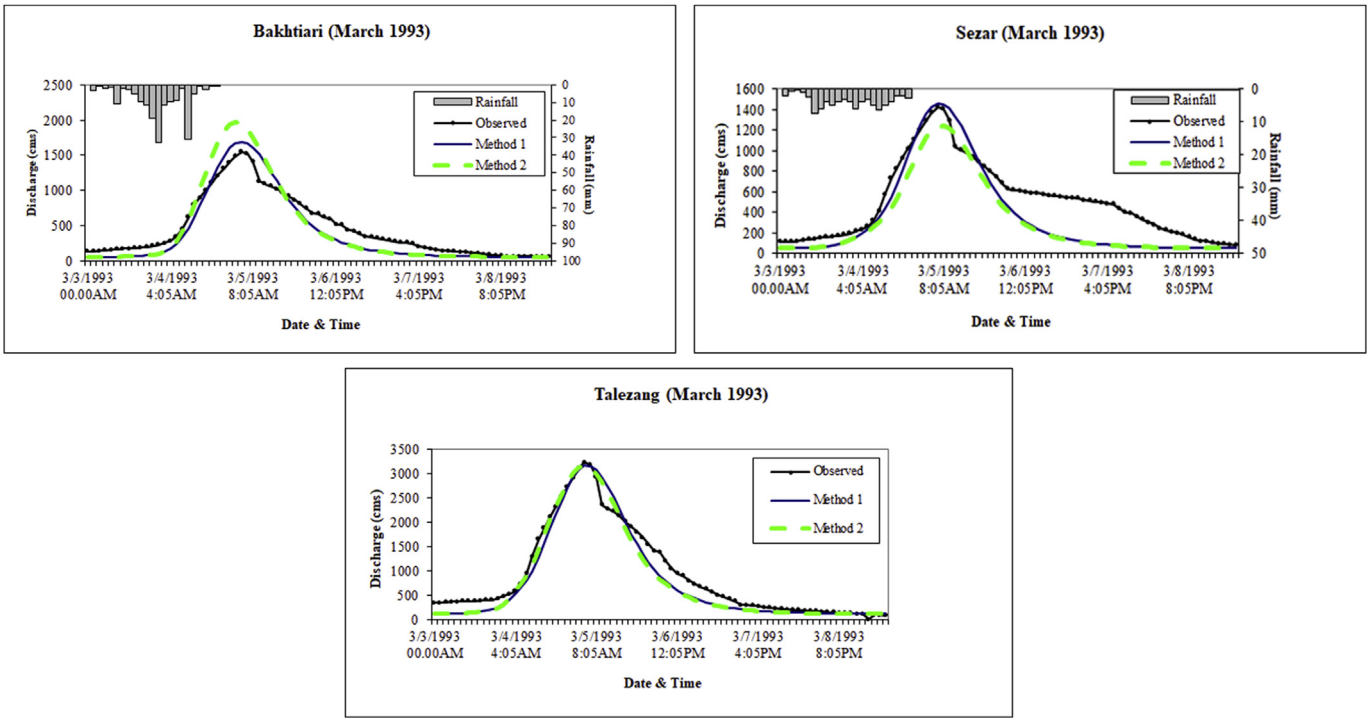


Fig. 8. Storm March 2, 1993, predicted vs. observed runoff hydrograph for sub-basins: (A) Bakhtiari, (B) Sezar and (C) Talezang.

hydrograph) is of secondary importance. This type of models has some limitations in their simulations, e.g., to estimate the base flow correctly due to the lack of consideration of wet/dry cycles in soils, and to take into account the vegetation cover and soil water storage (due to lack of soil texture), especially at the recession limb of the hydrograph which was seen in our results at verification step (Fig. 8). Although at the calibration step (2001 flood, Fig. 7), the model overestimated both hydrograph limbs (rising and falling). In addition to this weaknesses of the model, due to limited data for the study area, it is impossible to sub-divided Dez River basin into smaller sub-basins and it is difficult to eliminate this error by calibration. Thus, it is observed that the reported error values in Tables 5 and 7 are much lower than Table 6 (i.e., runoff volume errors). It means that efforts have been made to adapt the peak flow and time to peak values and since Hec-1 do not have the ability to consider soil moisture conditions, it can not work well in terms of the balance equation and does not estimate the amount of runoff properly. In short, the goodness criterion of this model is the relative error in the peak discharge estimation and time to peak. The overestimation of

Table 5
Observed peak flow, simulated peak flow and relative error.

Station		Flood event	Peak Flow (cms)[a]			Relative Error (%)[b]	
			Observed	Method 1	Method 2	Method 1	Method 2
Bakhtiari	1	30-Dec-2001	1944.0	1899.7	1983.8	−2.3	2.0
	2	2-Mar-1993	1551.0	1693.8	1976.7	9.2	27.4
Sezar	1	30-Dec-2001	1724.0	1729.8	1641.0	0.3	−4.8
	2	2-Mar-1993	1426.9	1458.5	1238.3	2.2	−13.2
Talezang	1	30-Dec-2001	3668.0	3643.3	3597.3	−0.7	−1.9
	2	2-Mar-1993	3165.6	3236.9	3172.1	2.3	0.2

Note: Negative and positive values of relative error indicate that the model predicted peak flow less and more than the observation peak flow.
[a] cms = cubic meter per second.
[b] Relative errors are computed based on Eq. (10).

flood volume in our modelling also exists in other modelling studies such as Knebl et al. (2005).

It can also be seen that simulation results for storms in both methods were good; but the model gave better performance in Method 1 compared to Method 2 (Table 5). A closer look at the estimation results by two searching methods (Methods 1 and 2) shows that for the Method 1, all sub-basins leads to good model performance and Method 2 had two hours error in March 1993 storm event in Bakhtiari and Sezar sub-basins (Table 7).

The peak flow of the first storm (Dec 30, 2001) with a duration of 44 h and intensity of 4.2 mm/h in the Bakhtiari sub-basin, has been predicted with only −2.3% error by Method 1 (i.e., 44.3 cms less than observation); whereas, Method 2 predicted the peak flow with +2% error (i.e., 39.8 cms more than observation). The time to peak was absolutely right for both methods (0% error), while the runoff volume was estimated with a significant error (i.e., 95.4 mcm or million cubic meter, about +57.5% error for Method 1; 105.3 mcm or million cubic meter, about +63.6% error for Method 2). In the Sezar sub-basin with a two hour less duration (42 h) and the intensity less than half of Bakhtiari (1.9 mm/h), the peak flow and runoff volume have been predicted with +0.3% and +62.5% error, respectively by Methods 1 (i.e., 5.8 cms and 89.9 mcm more than observation); whereas, Method 2 predicted with −4.8% and +54.8% error (i.e., 83 cms less and 78.9 mcm more than observation). The time to peak was absolutely right for both methods. In the Talezang Station, which was the outlet of the entire watershed, the prediction error for the peak flow was the smallest, with −0.7% for Method 1 as compared to the second method (Table 5). The time to peak was predicted with high accuracy of 0.0% and −3.4% for Methods 1 and 2, respectively. The runoff volume prediction error like upstream sub-basins in both methods were high around 60%.

After calibrating the model for the first flood (Dec 30, 2001), to verify the performance of the model, it was used with the same settings for the second flood (March 2, 1993). Table 2 shows the characteristics of the second events which was used for model verification.

The peak flow of the second storm (March 2, 1993) with a duration of 44 h and intensity of 3.9 mm/h in the Bakhtiari sub-basin, has been predicted with only +9.2% error by Method 1 (i.e., 142.8 cms more than observation); whereas, Method 2 predicted the peak flow with +27.4% error (i.e., 425.7 cms more than observation). The time to peak was predicted with high accuracy of 0.0% and −3.8% for Methods 1 and 2, respectively. Unlike to the calibration step, the runoff volume was estimated with a negligible error (i.e., 35.9 mcm, about −13.7% error for Method 1; 14.2 mcm, about −5.4% error for Method 2). In the Sezar sub-basin with a similar duration (44 h) and the intensity less than half of Bakhtiari (1.8 mm/h), the peak flow and runoff volume have been predicted with +2.2% and −29.0% error, respectively by Methods 1 (i.e., 31.6 cms more and 82.3 mcm less than observation); whereas, Method 2 predicted with −13.2% and −38.1% error (i.e., 188.6 cms and 108.1 mcm less than observation). The time to peak was predicted with high accuracy of 0.0% and +3.7% for Methods 1 and 2, respectively. In the Talezang Station, the predicted peak flow by Methods 1 and 2 was well with +2.3% and +0.2% errors, respectively. Methods 1 and 2 estimated the time to peak and runoff volume well with the same values of error, which were absolutely 0% and about −13%, respectively.

To better evaluate model performance (calibration and validation), statistical analysis was done for both rainfall events. Both storms had different rainfall intensities and depths in each sub-basin (Table 2) and occurred on different months and different years. Summary values of different efficiency criteria (coefficient of determination, R^2, and the index of agreement, IA) for both storm events are presented in Tables 8 and 9. The relative error (Z) of peak flow was generally minor by Method 1 (less than 10%) and the coefficient of determination (R^2) was

Table 6
Observed runoff volume, simulate runoff volume and relative error.

Station		Flood event	Runoff Volume (mcm)[a]			Relative Error (%)[b]	
			Observed	Method 1	Method 2	Method 1	Method 2
Bakhtiari	1	30-Dec-2001	165.7	261.1	271.0	57.5	63.6
	2	2-Mar-1993	262.8	226.9	248.6	−13.7	−5.4
Sezar	1	30-Dec-2001	143.9	233.8	222.8	62.5	54.8
	2	2-Mar-1993	284.1	201.8	176.0	−29.0	−38.1
Talezang	1	30-Dec-2001	322.9	519.8	511.4	61.0	58.4
	2	2-Mar-1993	521.4	451.2	448.8	−13.5	−13.9

Note: Negative and positive values of relative error indicate that the model predicted runoff volume less and more than the observation volume.
[a] mcm = million cubic meter.
[b] Relative errors are computed based on Eq. (11).

Table 7
Observed and simulated time to peak, and relative error.

Station		Flood event	Time to Peak			Relative Error (%)[a]	
			Observed	Method 1	Method 2	Method 1	Method 2
Bakhtiari	1	30-Dec-2001	12/2/2001 (08:05 a.m.)	12/2/2001 (08:05 a.m.)	12/2/2001 (08:05 a.m.)	0.0	0.0
	2	2-Mar-1993	03/5/1993 (04:05 a.m.)	03/5/1993 (04:05 a.m.)	03/5/1993 (02:05 a.m.)	0.0	−3.8
Sezar	1	30-Dec-2001	12/2/2001 (10:05 a.m.)	12/2/2001 (10:05 a.m.)	12/2/2001 (10:05 a.m.)	0.0	0.0
	2	2-Mar-1993	03/5/1993 (06:05 a.m.)	03/5/1993 (06:05 a.m.)	03/5/1993 (08:05 a.m.)	0.0	3.7
Talezang	1	30-Dec-2001	12/2/2001 (10:05 a.m.)	12/2/2001 (10:05 a.m.)	12/2/2001 (08:05 a.m.)	0.0	−3.4
	2	2-Mar-1993	03/5/1993 (04:05 a.m.)	03/5/1993 (04:05 a.m.)	03/5/1993 (04:05 a.m.)	0.0	0.0

Note: Negative and positive values of relative error indicate that the model predicted time to peak earlier and later than the observation time.
[a] Relative errors are computed based on Eq. (10).

Table 8
Model efficiency for simulation of December 2001 storm.

Sub-basin	Method	Efficiency	
		R^2	*IA*
Bakhtiari	1	0.49	0.85
	2	0.47	0.83
Sezar	1	0.53	0.84
	2	0.53	0.87
Talezang	1	0.41	0.82
	2	0.42	0.83

Note: Model efficiency was computed based on Eqs. (12) and (13).

Table 9
Model efficiency for simulation of March 1993 Storm.

Sub-basin	Method	Efficiency	
		R^2	*IA*
Bakhtiari	1	0.91	0.98
	2	0.89	0.96
Sezar	1	0.74	0.92
	2	0.74	0.91
Talezang	1	0.94	0.99
	2	0.94	0.99

Note: Model efficiency was computed based on Eqs. (12) and (13).

higher than 0.74 for storm March 1993 (Table 9), although it is somewhat less in the calibration step (i.e., 2001 flood), ranges between 0.41 and 0.53 (Table 8). The index of agreement (*IA*) is higher than 0.82 for all three sub-basins and both methods, however the qualitative comparison (Figs. 7 and 8) indicates the mismatch between the observational and simulated hydrographs (except at the peak point). It can also be seen that the simulation results for storms in March 1993 was better than December 2001. The index of agreement similar to coefficient of determination varies from 0.0 to 1.0, with higher values indicating better agreement between the model and observations. The high values of the Willmott's index (*IA*) and coefficient of determination (R^2) for storm 1993, which are above 0.91 and 0.74, respectively, indicate that the performance of the model is acceptable. However, in the calibration step, the performance of the model was slightly weaker. From Table 8 it is seen that, for the calibration data sets, the efficiency R^2 criterion, were 0.49, 0.53, and 0.41, respectively for Bakhtiari, Sezar and Talezang sub-basins by Method 1, whereas the index of agreement were 0.85, 0.84, and 0.82. In Method 2, the results are slightly different in the same range (see Table 8 for details). It seems that the model gave better performance in Method 1 compared to Method 2. As can be expected from the values of the evaluation criteria, the results showed that there was an overall agreement between observed and estimated peak discharges and the time of occurrences. In contrast, significant overestimation were observed in the calibration step (Fig. 7), but in the verification step (Fig. 8), a fairly good match was observed, and only the simulated flow was slightly underestimated at the rising and recession limb of the hydrographs.

A sensitivity analysis was also performed to help to determine which parameters have the greatest influence on the model results. The Curve Number (*CN*), the imperviousness percentage of drainage basin (*RTIMP*) and the initial rainfall abstraction (*STRTL*) parameters for the different sub-basins of the study area were used for sensitivity analysis of the model outputs (peak flow, time to peak and runoff volume). The range between ± 50 percent parameter perturbations was applied to all parameters except the curve number with a range between ± 10 percent. The results yielded from the sensitivity analysis for each sub-basin and method, are given in Tables 10–12. In these tables, columns two and three show the calibration parameter and their variations, respectively, while the upper part shows the calibrated values of the model for each sub-basin (base values). The next columns show the amount of changes in the peak flow, total volume and time to peak values, respectively, related to the calibrated values (base values) using Methods 1 and 2.

The zero values in the three columns represent 'no change' in the peak flow, hydrograph volume and time to peak, while the negative values represent decreases, and positive values represent increases. From Table 10 it is seen that, in Bakhtiari sub-basin using Method 1, 10% increase in the *CN* calibrated value induced 32.2%, and 13.4% increase in the peak flow and runoff volume, respectively, but 4.4% decreased in the time to peak prediction, whereas Method 2 with similar change, estimated the peak flow and runoff volume with 29.8% and 13.5% increase, respectively, and time to peak reduced about 7%. From Table 11 it is seen that, in Sezar sub-basin using Method 1, 10% increase in the *CN* calibrated value induced 37.6%, and 15.2% increase in the peak flow and runoff volume, respectively, but 4% decreased in the time to peak prediction, whereas Method 2 with similar change, estimated the peak flow and runoff volume with 51.7% and 21% increase, respectively, and time to peak reduced about 6.2%. Similarly, in Talezang sub-basin using Method 1, 10% increase in the *CN* calibrated value induced 20.6%, and 20.1% increase in the peak flow and runoff volume, respectively, but 5.9% decreased in the time to peak prediction, whereas Method 2 with similar change, estimated the peak flow and runoff volume with 23.8% and 22.3% increase, respectively, and time to peak reduced about 2.3% (Table 12). It seems that the Sezar sub-basin is more sensitive to the change in the *CN* values, which can be related to its larger area than other sub-basins.

The *STRTL* parameter placed second among factors influencing peak flow and runoff volume outputs. It can be seen that, ± 50% change in *STRTL* parameter, in Bakhtiari, Sezar and Talezang sub-basins, induced 20.8%, 38.4% and 19% maximum change on peak flow values, respectively and 23.7%, 38.5% and 19.3% maximum change on runoff volumes, respectively. The model results are not very sensitive to *RTIMP* parameter, where the ± 50% change in this parameter, in

Table 10
Sensitivity analysis results for Bakhtiari sub-basin (Methods 1 and 2).

		Variation	Peak flow		Volume		Time to peak	
			Method 1	Method 2	Method 1	Method 2	Method 1	Method 2
	Base value	0	1899.67	1983.75	261.1	271	56	56
	(Unit)	(%)	(cms)[a]		(mcm)[b]		(hr)	
Output parameters variations (%)								
Calibration parameters variations (%)	*CN*	−10	−22.7	−22.7	−12.2	−12.2	6	3.7
		−5	−11	−11.6	−6.61	−6.5	3.1	0.7
		5	16.4	14.5	6.1	6.2	−2	−4.6
		10	32.2	29.8	13.4	13.5	−4.4	−7
	RTIMP	−50	−2.9	−1.4	−4.1	−2	0	0
		−25	−1.5	−2.8	−2.1	−4	0	0
		25	1.5	1.4	2.1	2	0	0
		50	2.9	2.8	4.2	4.1	0	0
	STRTL	−50	19.3	18.9	23.7	23.2	0	0
		−25	9.9	9.6	11.6	11.4	0	0
		25	−10.4	−9.8	−11.1	−10.8	0	0
		50	−20.8	−20	−21.6	−21.2	0	0

[a] cms = cubic meter per second.
[b] mcm = million cubic meter.

Bakhtiari, Sezar and Talezang sub-basins, induced 2.9%, 6% and 4.7% maximum change on peak flow values, respectively and 4.2%, 8.6% and 6.7% maximum change on runoff volumes, respectively. Meanwhile, *STRTL* and *RTIMP* have no effect on time to peak values.

The role of the CN parameter in changing the peak flow discharge is almost greater than the other parameters, as the role of the *STRTL* parameter in changing the amount of runoff volume is greater than the others. If *CN* value has an error of more than 10% it will result in a big impact on the peak flow. Similarly, smaller error in CN (less than 5%) causes a smaller impact on the peak flow in Bakhtiari and Talezang Sub-basins. The *STRTL* parameter has a moderate effect on the peak flow estimation. It can be seen that ± 25% change in *STRTL* value, causing insignificant effect on the output results. It was shown that *STRTL* parameter has an inverse effect on the peak flow and overestimation of *STRTL* caused a decrease on the peak flow estimation. Nevertheless, *CN* has an inverse impact on time to peak. This means that by over-estimation of *CN*, time to peak estimates were less than the base time.

Tables 13–15 represent the sensitivity indices results for the input calibration parameters with regard to peak flow, runoff volume and time to peak, respectively. Like above, the sensitivity indices reveals that among the calibrated parameters, the *CN* value is the most sensitive parameter concerning the peak flow for both methods in all three sub-basins. The highest sensitivity is observed in the sub-basins of Sezar, Bakhtiari and Talezang, respectively; and except for the Bakhtiari sub-basin, in other sub-basins the sensitivity of the Method 2 (i.e., basin average) to *CN*'s values was greater than the Method 1 (gauge weight). The sensitivity of the estimated runoff volumes to the changes in the *STRTL* parameter is greater than the other parameters, and after *CN*,

Table 11
Sensitivity analysis results for Sezar sub-basin (Methods 1 and 2).

		Variation	Peak flow		Volume		Time to peak	
			Method 1	Method 2	Method 1	Method 2	Method 1	Method 2
	Base value	0	1729.82	1641	233.8	222.8	58	58
	(Unit)	(%)	(cms)[a]		(mcm)[b]		(hr)	
Output parameters variations (%)								
Calibration parameters variations (%)	*CN*	−10	−27.6	−33.2	−13.9	−16.1	5.5	6.4
		−5	−15.7	−16.2	−8.2	−8.3	2.8	2.9
		5	16.4	26.3	6.1	10.2	−1.8	−3.4
		10	37.6	51.7	15.2	21	−4	−6.2
	RTIMP	−50	−5.7	−6	−8.4	−8.6	0	0
		−25	−2.8	−3	−4.2	−4.3	0	0
		25	3	3	4.2	4.3	0	0
		50	5.8	6	8.4	8.6	0	0
	STRTL	−50	33.2	34.8	37.4	38.5	0	0
		−25	17	17.9	18.1	18.6	0	0
		25	−17.9	−18.7	−16.6	−16.9	0	0
		50	−36.8	−38.4	−31.4	−32.5	0	0

[a] cms = cubic meter per second.
[b] mcm = million cubic meter.

Table 12
Sensitivity analysis results for Talezang sub-basin (Methods 1 and 2).

	Base value	Variation	Peak flow		Volume		Time to peak	
			Method 1	Method 2	Method 1	Method 2	Method 1	Method 2
		0	271.987	202.495	24.9	17.6	44	34
	(Unit)	(%)	(cms)[a]		(mcm)[b]		(hr)	
Output parameters variations (%)								
Calibration parameters variations (%)	*CN*	−10	−23.8	−31	−18.6	−19.7	2	6.4
		−5	−13.2	−19.1	−9.9	−10.8	0	4.8
		5	9	8.3	9.4	10.1	−3.9	0.4
		10	20.6	23.8	20.1	22.3	−5.9	−2.3
	RTIMP	−50	−2.7	−4.7	−5.3	−6.7	0	0
		−25	−1.3	−2.3	−2.7	−3.3	0	0
		25	1.3	2.3	2.7	3.4	0	0
		50	2.7	4.7	5.3	6.7	0	0
	STRTL	−50	8.9	16.9	15.6	19.3	0	0
		−25	4.6	8.7	7.7	9.4	0	0
		25	−5.1	−9.3	−7.4	−8.9	0	0
		50	−10.8	−19	−14.5	−17.2	0	0

[a] cms = cubic meter per second.
[b] mcm = million cubic meter.

Table 13
Sensitivity indices SI for different model parameters, calculated for Bakhtiari sub-basin (Methods 1 and 2).

		Sensitivity Indices Tolerance (i)	SI Peak flow		SI Volume		SI Time to peak	
			Method 1	Method 2	Method 1	Method 2	Method 1	Method 2
Calibration parameters variations (%)	*CN*	5	0.274	0.273	0.127	0.127	0.051	0.053
		10	**0.549**	**0.525**	0.256	0.257	0.104	0.107
	RTIMP	25	0.03	0.042	0.042	0.06	0	0
		50	0.058	0.042	0.083	0.061	0	0
	STRTL	25	0.203	0.194	0.227	0.222	0	0
		50	0.401	0.389	0.453	0.444	0	0

Note: The most sensitive parameters are in bold.

Table 14
Sensitivity indices SI for different model parameters, calculated for Sezar sub-basin (Methods 1 and 2).

		Sensitivity Indices Tolerance (i)	SI Peak flow		SI Volume		SI Time to peak	
			Method 1	Method 2	Method 1	Method 2	Method 1	Method 2
Calibration parameters variations (%)	*CN*	5	0.321	0.425	0.143	0.185	0.046	0.063
		10	**0.652**	**0.849**	0.291	0.371	0.095	0.126
	RTIMP	25	0.058	0.06	0.084	0.086	0	0
		50	0.115	0.12	0.168	0.172	0	0
	STRTL	25	0.349	0.366	0.347	0.355	0	0
		50	0.700	0.732	0.688	0.71	0	0

Note: The most sensitive parameters are in bold.

this parameter (*STRTL*) is known as the most sensitive parameter in changing the peak flow discharges. The *RTIMP* parameter has a low effect on peak flow and runoff volumes, where the maximum is on Sezar sub-basin (e.g., 50% change in *RTIMP* induced the volume sensitivity index equal to 0.172 by Method 2, and the peak flow sensitivity index equal to 0.115 by Method 1). Both *STRTL* and *RTIMP* parameters have no effect on time to peak values, although the role of the *CN* parameter is also very small (e.g., 10% change in *CN* induced the maximum sensitivity index equal to 0.126 by Method 2).

4. Conclusion

Flood is one of the natural disasters which can take place in many areas. In this research, a new framework which integrates the Geographic Information System (GIS) with a lumped, event-based model, the Watershed Modelling System (WMS) for flood modelling was developed. It also interconnects the terrain models and the GIS software, with commercial standard hydrological model, HEC-1. The Dez River Basin (about 16,213 km^2) in Khuzestan province in IRAN was the domain of study because of the frequent occurrences severe flash

Table 15
Sensitivity indices SI for different model parameters, calculated for Talezang sub-basin (Methods 1 and 2).

		Sensitivity Indices Tolerance (i)	SI Peak flow		SI Volume		SI Time to peak	
			Method 1	Method 2	Method 1	Method 2	Method 1	Method 2
Calibration parameters variations (%)	*CN*	5	0.222	0.274	0.193	0.209	0.039	0.044
		10	**0.444**	**0.548**	0.387	0.420	0.079	0.087
	RTIMP	25	0.026	0.046	0.054	0.067	0	0
		50	0.054	0.094	0.106	0.134	0	0
	STRTL	25	0.097	0.18	0.151	0.183	0	0
		50	0.197	0.359	0.301	0.365	0	0

Note: The most sensitive parameters are in bold.

flooding in last half century. Two historical storms, one from 29 November to 5 December 2001 used for the calibration stage, another from 2 to 7 March 1993 used for model verification. Transformation of storm events to runoff has been done using two different methods to determine the hyetographs which is the one parts of hydrologic process, i.e., gauge weight (Method 1) and basin average (Method 2).

In this type of hydrological modelling (flood prediction), the goal is to estimate the peak flow and time to peak, but the runoff volume or shape of hydrograph is of secondary importance. The best fit between the simulation and measurement was obtained in the model when Method 1 was used. At verification stage, a fairly good match was observed, and only the simulated flow was slightly underestimated at the rising and recession limb of the hydrographs, but significant overestimations were observed in the calibration stage. It means that, the model is incapable of estimating the shape of the hydrograph. In addition to the lack of data in the study area, the other reasons that such models have some limitations in their simulations, as follows: (1) incorrect estimation of the base flow due to the lack of consideration of wet/dry cycles in soils, (2) not including the vegetation cover and soil water storage due to lack of soil texture, etc.

The efficiency of the model was measured with R^2 correlation analysis and Willmott's index of agreement. The average efficiency (*IA*) for Methods 1 and 2 were found to be both 0.84 for calibration stage and 0.96 and 0.95, respectively for verification stage; whereas the coefficient of determination (R^2) was higher than 0.74 for storm March 1993 (verification), and ranges between 0.41 and 0.53 for storm December 2001 (calibration).

Finally, two different sensitivity analyses were performed for the three sub-basins in Dez River basin. Based on the sensitivity analysis, *CN* was found to be the most important parameter in defining the peak flow, runoff volume and time to peak values for all methods in the three sub-basins and it was found that, the Sezar sub-basin is more sensitive to the change in the *CN* values, e. g, an underestimation and overestimation of 10% about the base *CN* values, induced 27.6%, and 13.9% decreases and 37.6%, and 15.2% increases of peak flow, and total runoff volume, respectively by Method 1. On the other hand, *CN* has an opposite impact on time to peak, i.e. an overestimation and underestimation of 10% in *CN* values, induced 4% decrease and 5.5% increase on time to peak, respectively. After that the *STRTL* parameter had more impacts on the peak flow estimation and the total runoff volume as compared to *RTIMP* for all sub-basins and methods. Method 2 was identified as the most sensitive method for all parameters and sub-basins. In general, it can be concluded that although the lack of adequate precipitation gauge and rainfall data in this study, the hydrologic model performed well and can be applied to catchments with similar characteristics where lack of data exist.

Acknowledgement

We would like to express our thanks to the University of Tehran, for providing Watershed Modelling System (WMS) software, Soil Conservation and Watershed Management Research Institute, Ministry of Jihad-e-Agriculture, Iran, for providing the land use/land cover data, the topography map, and DEM (Digital Elevation Map). Thanks are also due to Mr. Katani and Mr. Rezazade from Dezab Consulting Engineers Company in Khuzestan province, Iran for providing Dez river data. We would like to thank Mr. Babaee from Iran Water Resources Management Company for providing the rain gauge and streamflow data. We would also like to thank the reviewers for helpful and constructive comments.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.pce.2018.07.003.

References

Beard, L.R., 1967. HEC-1, Flood Hydrograph Package. Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, California.
Berthet, L., Andréassian, V., Perrin, C., Javelle, P., 2009. How crucial is it to account for the antecedent moisture conditions inflood forecasting? Comparison of event-based and continuous approaches on 178 catchments. Hydrol. Earth Syst. Sci. 13819–13831. https://doi.org/10.5194/hess-13-819-2009.
Beven, K.J., 2001. Rainfall-runoff Modelling: the Primer. John Wiley & Sons, England.
Bhaskar, N.R., Brummett, L.K., French, M.N., 2005. Runoff modelling of a mauntainous catchment using TOPMODEL: a case study. J. Am. Water Resour. Assoc. 41 (1), 107–121.
Boughton, W., 2005. Catchment water balance modelling in Australia 1960-2004. Agric. Water Manag. 71 (2), 91–116.
Boughton, W., 2006. Calibrations of a daily rainfall-runoff model with poor quality data. Environ. Model. Software 21 (8), 1114–1128.
Brigham Young University, 2002. WMS v7.0 Help. Environmental Modelling Research Laboratory, Provo, UT.
Bürger, C.M., Kolditz, O., Fowler, H.J., Blenkinsop, S., 2007. Future climate scenarios and rainfall-runoff modelling in the Upper Gallego catchment (Spain). Environ. Pollut. 148 (3), 842–854.
Caruso, B.S., Rademaker, M., Balme, A., Cochrane, T.A., 2013. Flood modelling in a high country mountain catchment, New Zealand: comparing statistical and deterministic model estimates for ecological flows. Hydrol. Sci. J. 58 (2), 328–341.
Clarke, R.T., 1973. Mathematical Models in Hydrology. Irrigation and Drainage Paper 19. FAO, Rome, Italy.
Coustau, M., Bouvier, C., Borrell-Estupina, V., Jourde, H., 2012. Flood modelling with a distributed event-based parsimonious rainfall–runoff model: case of the karstic Lez river catchment. Nat. Hazards Earth Syst. Sci. 12 (4), 1119–1133.
de Roo, A.D.J., 1993. Modelling surface runoff and soil erosion in catchments using geographical information systems, Validity and applicability of the "ANSWERS" model in two catchments in the loess area of South Limburg (The Netherlands) and one in Deven (UK). Netherlands Geographical Studies 157 295 pp.
Devak, M., Dhanya, C.T., 2017. Sensitivity analysis of hydrological models: review and way forward. Journal of Water and Climate Change. https://doi.org/10.2166/wcc.2017.149. (in press).
Devia, G.K., Ganasri, B.P., Dwarakish, G.S., 2015. A review on hydrological models. Aquatic Procedia 4, 1001–1007.
Duru, J.O., Hjelmfelt, A.T., 1994. Investigating prediction capability of HEC-1 and KINEROS kinematics wave runoff models. J. Hydrol. 157 (1–4), 87–103.
EMSI, 2008. Available from: environmental modeling systems incorporated (EMSI). http://www.ems-i.com/WMS/WMS_Overview/wms_overview.html.
Giertz, S., Diekkrüger, B.D., Steup, G., 2006. Physically-based modelling of hydrological processes in a tropical headwater catchment (West Africa) – process representation and multi-criteria validation. Hydrol. Earth Syst. Sci. Discuss. 3, 1–57.
Gupta, H.V., Clark, M.P., Vrugt, J.A., Abramowitz, G., Ye, M., 2012. Towards a

comprehensive assessment of model structural adequacy. Water Resour. Res. 48, 1–16. https://doi.org/10.1029/2011WR011044.
Haubner, S., Reese, A., Brown, T., Claytor, R., Debo, T., 2001. Georgia Stormwater Management Manual, Volume 2, Technical Handbook, first ed. (Prepared for the Atlanta Regional Commission).
Hill, P.I., Mein, R.G., 1996. Incompatibilities between storm temporal patterns and losses for design flood estimation. In: Hydrology and Water Resources Symposium. Institution of Engineers, Hobart, Australia, pp. 445–451.
Hino, M., Odaka, Y., Nadaoka, K., Sato, A., 1988. Effect of initial soil moisture content on the vertical infiltration process – a guideto the problem of runoff-ratio and loss. J. Hydrol. 102 (1), 267–284.
Hoseini, Y., Azari, A., Pilpayeh, A., 2017. Flood modeling using WMS model for determining peak flood discharge in southwest Iran case study: simili basin in Khuzestan Province. Applied Water Science 7 (6), 3355–3363.
Hydrologic Engineering Center, 1998. HEC-1, Flood Hydrograph Package, User's Manual, Version 4.1. U.S. Army Corps of Engineers, CA.
Knebl, M.R., Yang, Z.L., Hutchison, K., Maidment, D.R., 2005. Regional scale flood modelling using NEXRAD rainfall, GIS, and HEC-HMS/RAS: a case study for the san antonio river basin summer 2002 storm event. J. Environ. Manag. 75, 325–336.
Legates, D.R., McCabe Jr., G.J., 1999. Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. Water Resour. Res. 35 (1), 233–241.
Loliyana, V.D., Patel, P.A., 2015. Lumped conceptual hydrological model for Purna river basin, India. Sādhanā 40 (8), 2411–2428.
Maidment, D.R., 1993. GIS and hydrological modelling. In: Goodchild, M.F., Parks, B.O., Steyaert, L.T. (Eds.), Environmental Modelling with GIS. Oxford University Press, New York, pp. 147–167.
Massari, C., Brocca, L., Barbetta, S., Papathanasiou, C., Mimikou, M., Moramarco, T., 2014. Using globally available soil moisture indicators for flood modelling in Mediterranean catchments. Hydrol. Earth Syst. Sci. 18 (2), 839–853.
Moradkhani, H., Sorooshian, S., 2008. General Review of Rainfall-runoff Modeling: Model Calibration, Data Assimilation, and Uncertainty Analysis. Hydrological Modeling and the Water Cycle. Springer 291 p. ISBN 978-3-540-77842-4.
Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models, I. A discussion of principles. J. Hydrol. 10, 282–290.
Pool, S., Vivirolia, D., Seiberta, J., 2017. Prediction of hydrographs and flow-duration curves in almost ungauged catchments: which runoff measurements are most informative for model calibration? J. Hydrol 554, 613–622.
Rogelis, M.C., Werner, M., Obregón, N., Wright, N., 2016. Hydrological model assessment for flood early warning in a tropical high mountain basin. Hydrol. Earth Syst. Sci. Discuss. 1–36. https://doi.org/10.5194/hess-2016-30.
Sadrolashrafi, S.S., 2008. Integrated Modelling for Flood hazard Mapping for Arid Region Using Watershed Modeling System. M.Sc. Thesis. School of Graduate Studies, Universiti Putra Malaysia, , Malaysia.
Singh, V.P., 1995. Computer Models of Watershed Hydrology. Water Resources Publications, Highlands Ranch, Colo., USA.
Singh, V.P., Woolhiser, D.A., 2002. Mathematical modelling of watershed hydrology. J. Hydrol. Eng. 7 (4), 270–292.
Sourinejad, A., 2008. Evaluation of the flooding intensity of the catchment area of southwest rivers of Iran (Case study: Dez river basin). In: Proceedings of the 2nd National Conference on Dam and Hydroelectric Power Plants, Iran Water and Power Resources Development Company, 15–16 May 2008, Tehran, Iran (In Persian).
Stewart, E.J., 2003. Development of a Distributed Hydrologic Model with Application to a Flood Alert System. M.Sc Thesis. RICE University, Houston, Texas.
Tramblay, Y., Bouvier, C., Martin, C., Didon-Lescot, J.-F., Todorovik, D., 2010. Assessment of initial soil moisture conditions forevent-based rainfall–runoff modelling. J. Hydrol 387 (3–4), 176–187.
Tramblay, Y., Bouaicha, R., Brocca, L., Dorigo, W., Bouvier, C., Camici, S., Servat, E., 2012. Estimation of antecedent wetnessconditions for flood modelling in northern Morocco. Hydrol. Earth Syst. Sci. Discuss. 9 (8), 9361–9390.
US Soil Conservation Service, 1972. National Engineering Handbook, Section 4. Hydrology. Department of Agriculture, Washington 762 p.
US Soil Conservation Service, 1986. Urban Hydrology for Small Watersheds (Technical Release 55). US Department of Agriculture, Washington 164 p.
Van Steenbergen, N., Willems, P., 2013. Increasing river flood preparedness by real-time warning based on wetness stateconditions. J. Hydrol. 489, 227–237. https://doi.org/10.1016/j.jhydrol.2013.03.015.
Vertessy, R., Elsenbeer, H., Bessard, Y., Lack, A., 2000. Storm runoff generation at La Cuenca. In: Grayson, R., Bloschl, G. (Eds.), Spatial Patterns in Catchment Hydrology: Observations and Modeling. Cambridge University Press, Cambridge, United Kingdom.
Wagener, T., Wheater, H.S., Gupta, H.V., 2004. Rainfall-runoff Modelling in Gauged and Ungauged Catchments. Imperial College Press, London.
Willmott, C.J., 1981. On the validation of models. Phys. Geogr. 1, 184–194.
Zhang, D., Zhang, L., Guan, Y., 2012. Sensitivity analysis of Xinanjiang rainfall–runoff model parameters: a case study in Lianghui, Zhejiang province, China. Nord. Hydrol 43, 123–134.